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Impact of Sampling Rate Reduction on Automatic ECG Delineation

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Abstract— **Electrogram (EGM) delineation is an increasingly important task to be performed in implantable cardiac devices such as pacemakers and defibrillators. Reliable detection and classification of EGM components might help to minimize the risk of false detections. Efforts are therefore undertaken to examine whether existing ECG delineators can be adapted for the delineation of EGMs. One issue to be solved is the low sampling rate at which EGMs are acquired. In this study we investigate performance degradation of an existing wavelet-based ECG delineator by a stepwise reduction of the sampling rate. It is shown that for signals sampled at 1 kHz, no significant performance degradation occurs in P or T wave delineation. The performance of QRS delineation is affected only at the lowest sampling rate of 62.5 Hz. For signals originally sampled at 250 Hz, no degradation in delineation performance is observed.**

It is concluded that the automatic delineation of ECGs can be performed at sampling rates as low as 62.5 Hz and that the low sampling rate does not significantly degrade the reliability of automatic delineation.

I. INTRODUCTION

Most of today's implantable cardiac devices such as pacemakers and defibrillators are equipped with algorithms that make decisions based on sensed cardiac events. The introduction of real-time digital signal processing technology has added a new dimension to cardiac signal analysis. Besides conventional event-based decisions, digital signal processing enables morphological analysis of the electrogram (EGM), including characterization of the individual components. This development not only enables new sensing applications but may also reduce false detections.

Since electrograms are in nature similar to surface ECGs, existing ECG delineation techniques are good candidates to analyze EGMs. However, to optimize delineation performance there are several issues that need specific attention. First, the ECG and EGM have some morphological differences, i.e. characteristic components of the ECG are not necessarily present in the EGM. Moreover, the spectral content of the EGM differs from that of the ECG. Since this affects any filtering-based approach including wavelet based delineation, spectral analysis is required to reveal the relevant differences. Finally, there are several technical constraints that lead to marked differences between electrograms and the surface ECG. Most critical is the low sampling rate at which EGMs are typically acquired due to the limited power budget and storage capacity. The present work aims to investigate this issue by studying the degradation in delineation performance when applying a wavelet-based ECG delineator recently described by Martinez *et al.* [1] on datasets with stepwise reduced sampling rates. In addition, initial morphological and spectral differences between the ECG and EGM are studied.

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II. MATERIALS AND METHODS

A. Signal Databases

Automatic delineation was performed on two publicly available signal databases.

1) PTB Diagnostic ECG Database (PTBDB): contains 549 high-resolution 15-lead ECG recordings (12 standard leads together with Frank XYZ leads) sampled at 1 kHz, having a resolution of 0.5 μV and being of variable duration [3], [4]. The recordings include 54 healthy controls and 240 patients with different cardiopathies. The delineation was performed on beats from the lead II signal, manually selected and annotated for QRS onset and T wave end by 5 experts individually as described by Christov *et al.* [5]. The median of the 5 expert annotations was considered the gold standard.

2) QT Database (QTDB): contains 105 two-lead (mostly MLII and V5) ECG recordings of 15 minutes each acquired at a sampling rate of 250 Hz [6]. In each recording, a minimum of 30 consecutive beats were annotated by an expert cardiologist for the onset, peak, and end of the P, QRS, T, and (where present) U wave. P waves were annotated on 3335 beats, QRS delineation on 3623 beats, and T wave delineation on 3542 beats. Eleven recordings were also annotated by a second cardiologist.

B. QRS detection and wave delineation

Automatic waveform delineation of the ECG was performed by a multiscale wavelet-based ECG delineator previously described and validated [1]. Detection of all fiducial points (onset, peak and end) of the ECG components was based on the quadratic spline wavelet transform producing smoothed ECG derivatives at four dyadic scales.

C. Signal downsampling

To evaluate the effect of sampling frequency reduction on delineation performance, the signals in the PTBDB were consecutively downsampled by a factor 2, 4, 8 and 16, thus obtaining ECG signals sampled at 500, 250, 125 and 62.5 Hz, respectively. The QTDB signals, originally sampled at 250 Hz, were downsampled only by a factor 2 and 4.

D. Evaluation of the delineation performance

Delineation performance was evaluated as the difference (mean ± SD) between automatic detection and median expert annotation. The inter-expert variability was calculated as the mean ± SD between the individual expert annotation and the median (PTBDB) or mean (QTDB) expert annotation. The delineation tolerances reported in [7] are also used for comparison purposes.

In the PTBDB, the delineator was applied to lead II. In the QTDB, the delineation was run on leads MLII and V5. For each point, the annotation with lowest error was selected.

In automatic ECG delineation, large errors are usually associated with missed waves, whereas small errors relate to the delineation accuracy in waves with morphologies correctly identified. Because this study will primarily focus on reduction of delineation accuracy at lower sampling rates, performance was also estimated exclusively on correctly delineated beats at the highest sampling rate. Therefore beats with a QRS onset error >10 ms and a T wave end error exceeding 30 ms were excluded.

E. Spectral analysis

Power spectra were obtained by computing the average fast-Fourier transform on a selected number of beats.

1) ECG: 300 normal sinus rhythm beats were randomly selected from the MIT-BIH Arrhythmia Database, consisting of 48 fully annotated recordings sampled at 360 Hz with an 11-bit resolution over a 10 mV amplitude range [2].

2) EGM: 18 normal sinus rhythm beats were selected from an electrogram database containing EGM from implantable cardioverter defibrillators and comprised recordings of heart beat rhythm prior and after therapy delivery. These signals were recorded unipolarly (between the device and the ring of the ventricular lead) at 64 Hz with a 12-bit resolution over a 8 mV range.

III. RESULTS

A. PTBDB

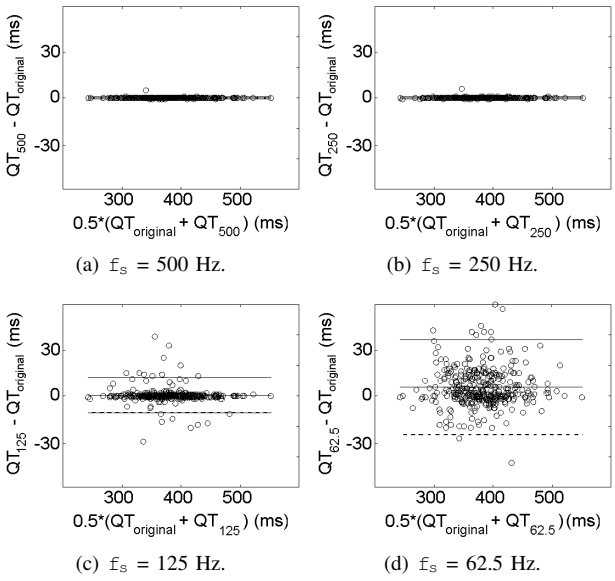
Automatic delineation was successful in 471 out of 549 beats. We excluded 37 records in which the annotated beat was the first one, 35 beats due to false-positive detections and 6 because of false-negative detections of QRS fiducial points. In Table I (first and second column), the delineation errors at the various sampling rates are shown for QRS onset and T wave end. The inter-expert variability is included for comparison.

The third and fourth column summarize the results after omitting measurements with large delineation error at 1 kHz. In this situation, QRS onset was performed on 375 records and T wave detection on 390 records correctly delineated at 1 kHz.

TABLE I

DELINEATION ERRORS IN RECORDS OF THE PTBDB (IN MS)

	All beats		With error thresholding	
f_S (Hz)	QRS onset	T end	QRS onset	T end
1000	-4.5 ± 11.0	2.9 ± 33.1	-2.6 ± 4.5	1.5 ± 12.3
500	-4.4 ± 10.7	2.9 ± 33.1	-2.6 ± 4.5	1.5 ± 12.3
250	-4.4 ± 10.7	2.9 ± 33.1	-2.6 ± 4.5	1.5 ± 12.3
125	-4.6 ± 11.5	2.8 ± 33.3	-3.0 ± 7.0	1.3 ± 12.6
62.5	-8.1 ± 14.1	3.2 ± 33.2	-7.9 ± 13.2	1.6 ± 13.6
Experts [5]	0.0 ± 3.2	0.0 ± 8.0	-0.5 ± 3.1	0.1 ± 7.5
Toler. [7]	$- \pm 6.5$	$- \pm 30.6$	$- \pm 6.5$	$- \pm 30.6$



(a) f_S = 500 Hz. (b) f_S = 250 Hz.

(c) f_S = 125 Hz. (d) f_S = 62.5 Hz.

Fig. 1. Bland-Altman plots for error measurement at the PTBDB.

To evaluate delineation performance on other ECG components, we compensated for the absence of expert annotations by taking the automatic detections at 1 kHz as a reference. This enabled the additional delineation of P wave onset, P wave end, QRS end and T wave onset (Table II).

The Bland-Altman plots in Fig. 1 illustrate the agreement between QT interval estimation for downsampled signals and original signals.

B. QTDB

In this database, delineation of the P wave was successful in 94.96% (n=3335), QRS delineation in 99.99% of the cases (3622 out of 3623 beats) and T wave delineation in 99.78% (3534 out of 3542 beats). These numbers did not change as sampling rates were reduced.

Table III summarizes the results of the automatic delineation at all sampling rates compared to expert annotations. The agreement between QT measurements at original and downsampled signals is shown in Fig. 2 by means of Bland-Altman plots.

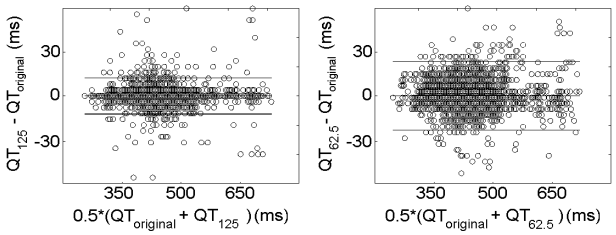
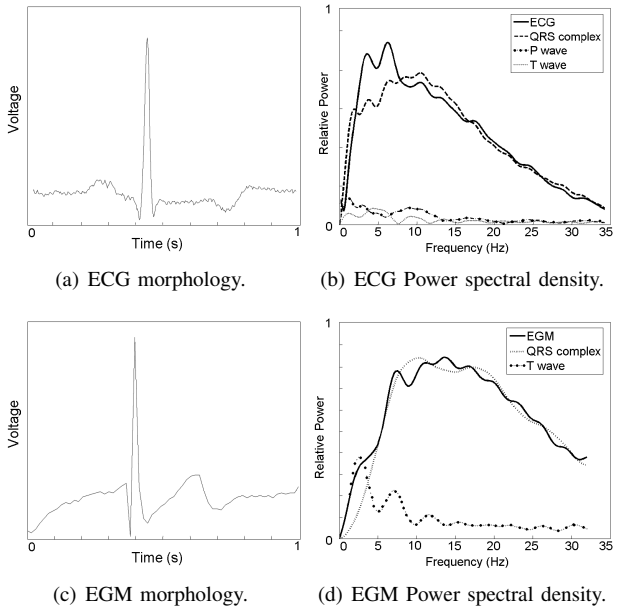


Fig. 2. Bland-Altman plots for error measurement at the QTDB.



(a) ECG morphology. (b) ECG Power spectral density.

(c) EGM morphology. (d) EGM Power spectral density.

Fig. 3. Time and frequency plots for the ECG and EGM. (a) Typical morphology of a single beat of normal sinus rhythm ECG. Visible are the P wave, QRS complex and T wave; (b) Power spectral density function (PSD) computed on the average of 300 beats of normal sinus rhythm ECG. (c) Morphology of a single beat of normal sinus rhythm EGM recorded unipolarly from a ventricular lead. Visible components include the QRS complex and T wave. (d) PSD computed on the average of 18 beats of normal sinus rhythm EGM acquired from a unipolar ventricular lead.

C. Morphological and spectral analysis

Time and frequency plots for ECG and EGM are shown in Fig 3. The time series in the panel a) and c) show the typical morphology of a single beat of ECG and EGM recorded during normal sinus rhythm. Panels b) and d) contain the power spectral density functions (PSD) for the ECG and EGM, and their main components.

IV. Discussion and conclusion

The main objective of the present work was to quantify the impact of reduced sampling rates, as used for EGM recording in implantable devices, on the performance of a wavelet-based ECG delineator.

Table I shows that the error in QRS onset detection remains essentially constant when downsampling from the original frequency (1000 Hz) down to 125 Hz, but it markedly increases at 62.5 Hz (the QRS onset detection is located on average 4 ms before those at higher sampling rates and the standard deviation increases from 11 ms to 14 ms).

When focusing on beats well delineated at 1000 Hz, a degradation in QRS onset delineation is already observed at 125 Hz. On the other hand, the T wave end delineation error is similar at all sampling frequencies. The error is substantially higher in the case of T wave end than in QRS onset, as could be expected.

The degradation in delineation performance of the QRS onset can be attributed to the loss of high-frequency components of the QRS complex at lower sampling rates. The T wave end error does not increase significantly since the low-frequency content of the T wave is preserved even at a sampling rate of 62.5 Hz.

For ECG fiducial points other than the QRS onset and T wave end, similar conclusions can be derived from Table II. QRS delineation is most notably affected by the sampling rate reduction.

The results of the QTDB delineation show that the error remains fairly constant for all fiducial points. In contrast to the PTBDB, the SD of the QRS onset delineation does not increase at 62.5 Hz, as shown in Table III. As can be seen in Fig. 2, QT interval estimations at 62.5 Hz are less stable than at 125 Hz. However, this increased variability is negligible compared to the SD at the original sampling frequency.

The differences in the results obtained in both databases could be explained by the different equivalent recording cutoff frequencies that were used (500 Hz in the PTBDB vs 100 Hz in the QTDB).

Acceptable limits for automatic delineation errors are usually based on comparison with inter-expert variability. In the case of the PTBDB the variability between the five expert annotators is much lower than the error obtained by automatic delineation, as well as the inter-expert error found in other studies [1] or the tolerances proposed in [7]. This may be explained as being the result of the three-round feedback procedure that was used to reduce the largest discrepancies between expert annotators [5]. In the PTBDB, T wave end delineation errors are in the order of the CSE-proposed tolerances, while QRS onset delineation errors are larger even at the original sampling frequency, and even more pronounced at 62.5 Hz. Most large QRS onset errors are due to misinterpretation of small Q waves. However, in the QTDB, the differences of automatic delineation, even at 62.5 Hz, are below the inter-cardiologist differences at the same database.

From the results obtained in the PTBDB and QTDB ECG databases, it can be concluded that the delineation remains essentially unaffected for sampling frequencies higher than 125 Hz, while a slight but not negligible loss in delineation accuracy of the waves with higher frequency content, i.e. the QRS complex is observed when sampling at 62.5 Hz.

Before adapting the wavelet-based ECG delineator to EGMs, it is important to identify morphological and spectral differences between both signals. However, the shape of the EGM signal is strongly affected by the lead configuration. Unipolar EGMs differ from bipolar EGMs and signals

TABLE II

DELINEATION ERRORS WITH RESPECT TO THE AUTOMATIC DETECTIONS AT 1000 HZ OF THE PTBDB (IN MS)

f_s (Hz)	P onset	P end	QRS onset	QRS end	T onset	T end
500	0.0 ± 0.1	0.0 ± 0.1	0.1 ± 2.4	0.0 ± 1.0	0.0 ± 0.1	0.0 ± 0.1
250	-0.1 ± 2.9	0.0 ± 0.4	0.1 ± 2.5	0.1 ± 1.0	0.0 ± 0.3	0.0 ± 0.3
125	0.0 ± 5.4	0.2 ± 4.0	-0.1 ± 6.7	0.1 ± 7.7	0.0 ± 4.7	0.0 ± 3.2
62.5	-0.7 ± 14.4	0.1 ± 11.5	-3.6 ± 16.3	3.4 ± 17.5	-0.4 ± 8.9	0.4 ± 7.4

TABLE III

DELINEATION ERRORS WITH EXPERT ANNOTATIONS AS REFERENCE OF THE QTDB (IN MS).

f_s (Hz)	P onset	P end	QRS onset	QRS end	T peak	T end
250	2.0 ± 15.0	1.9 ± 12.9	4.6 ± 7.7	0.8 ± 8.7	0.2 ± 13.9	-1.6 ± 18.1
125	2.2 ± 14.7	1.9 ± 12.7	4.7 ± 7.7	0.9 ± 8.5	0.3 ± 13.9	-1.5 ± 18.5
62.5	2.5 ± 14.5	2.4 ± 13.6	4.0 ± 7.6	1.0 ± 8.4	0.1 ± 13.8	-1.5 ± 17.8
Inter − cardiol	–	–	5.3 ± 11.1	-0.1 ± 12.2	5.1 ± 15.9	2.1 ± 22.4
Tol. [7]	$- \pm 10.2$	$- \pm 12.7$	$- \pm 6.5$	$- \pm 11.6$	–	$- \pm 30.6$

recorded from a ventricular lead are very distinct from those recorded atrially. We therefore consider only one type of configuration here: the unipolar EGM of a ventricular lead. The time domain plots in Fig. 3 show that morphological differences can be found in the lack or presence of a P wave and the individual deflections of the QRS complex. In the spectral domain, the PSD plots show that the peak signal power is similarly distributed for the entire beat as well as for QRS complex and T wave components. This suggests that a wavelet-based approach for EGM delineation, similar to that described in [1], may be effective for EGM signals.

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